Indirect Searches for New Physics in Rare Kaon Decays

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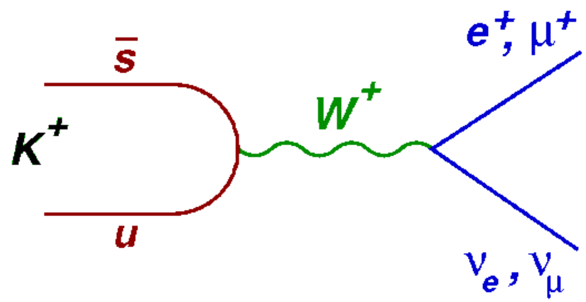
Introduction

- Precise measurements of FCNC processes in the B sector have severely restricted the parameter space of new-physics models
- Experiments at the LHC have started a direct exploration of the physics in the TeV range
- In this scenario, rare kaon decays are an outstanding opportunity to search for NP effects complementary to the high energy frontier and to the precision B physics

$R_K=\Gamma(K\to e\nu)/\Gamma(K\to\mu\nu)$ in the SM

- The decay $K\to e\nu$ is helicity suppressed



- In the ratio $R_K = \Gamma(K\to e\nu / K\to\mu\nu)$ hadronic uncertainties cancel
- The SM prediction of R_K has reached <0.1% precision

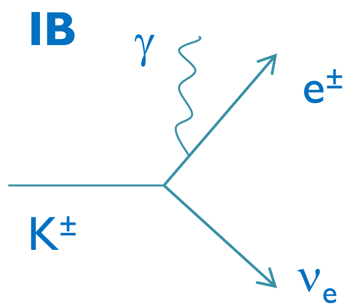
$$\mathrm{R}_{\mathrm{K}}^{\mathrm{SM}} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \left(1+\delta R_K^{\mathrm{rad.corr.}}\right) = (2.477 \pm 0.001) \times 10^{-5}$$

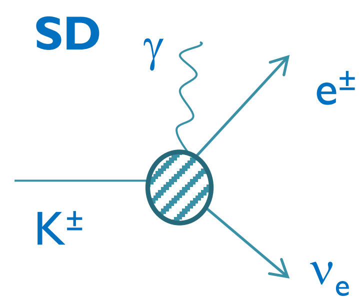
[V. Cirigliano and I. Rosell Phys. Rev. Lett. 99 (2007) 231801]

- δR_K is the correction due to the Inner Bremsstrahlung part of the radiative $K \to e\nu\gamma$ process

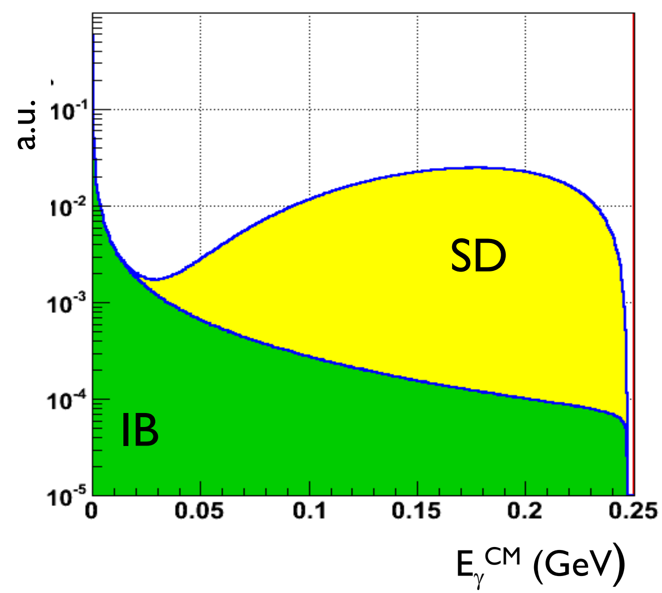
Radiative $K \rightarrow e\nu\,\gamma$ Decays

- In $K \rightarrow e\nu\,\gamma$ ($K_{e2\gamma}$), γ can be produced via internal bremsstrahlung (IB) or direct-emission (SD)





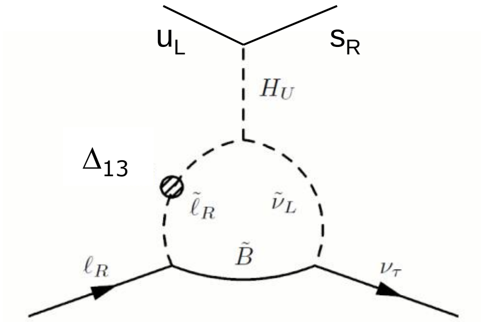
- By definition R_K is inclusive of IB radiation only



R_K beyond the SM

- In MSSM, sizable sources of flavour violation in the lepton sector (Δ_{13}~10^{-4}) can induce deviation from R_K^{SM} at % level (e.g. $\tan\beta$=40, m_H=500 GeV/c^2)

[A. Masiero, P. Paradisi, R. Petronzio Phys. Rev. D74 (2006) 011701]



$$R_K^{LFV} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \cong \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}$$

$$R_K^{LFV} = R_K^{SM}\left[1 + \left(\frac{m_K}{m_H}\right)^4 \left(\frac{m_\tau}{m_e}\right)^2 |\Delta_{13}|^2 \tan^6\beta\right]$$

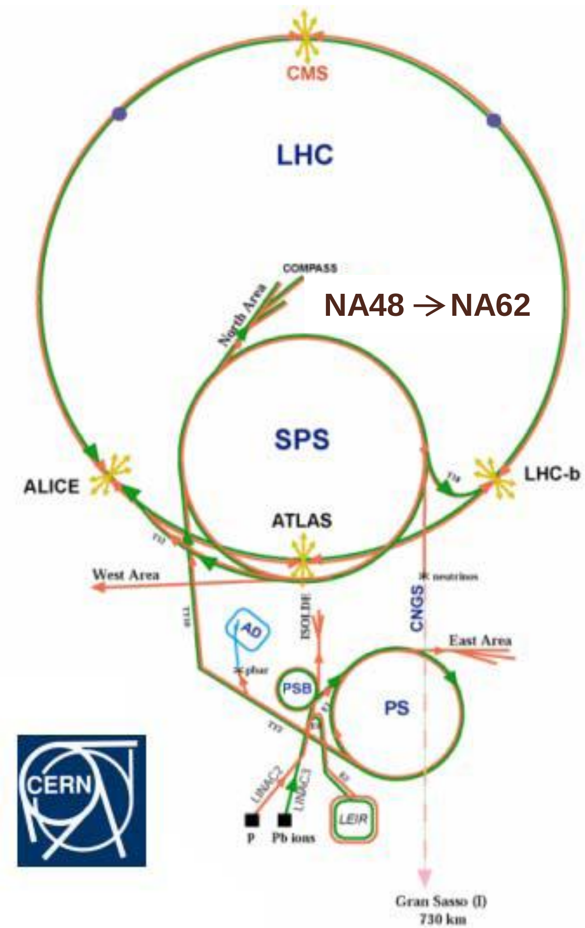
- Larger effects foreseen in B decays due to $(m_B/m_K)^4$~10^4 but experimentally challenging

The NA62 experiment

A fixed target experiment at the CERN SPS

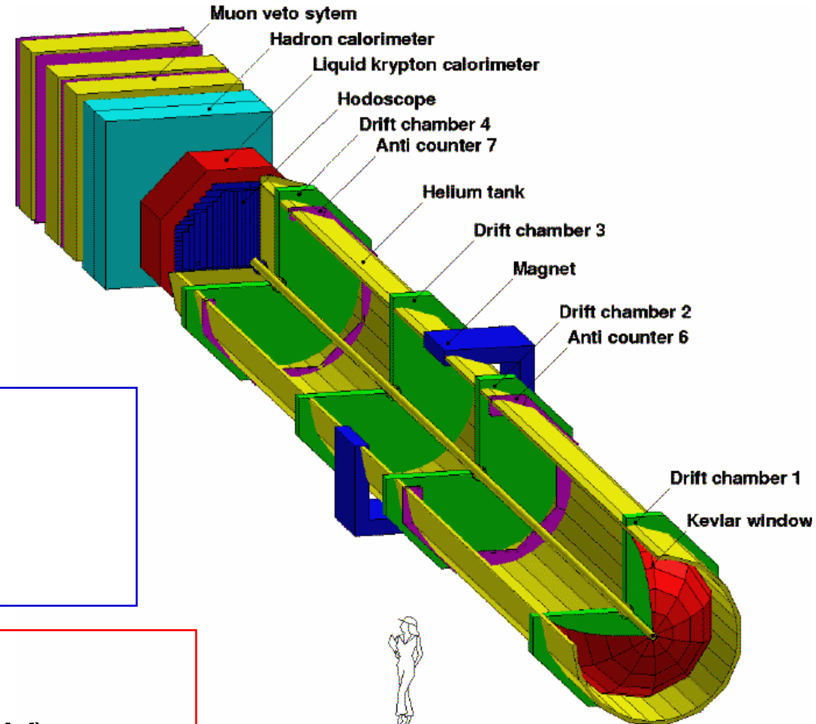
The SPS is needed as LHC proton injector only part-time

For the remainder of the time it can provide 400 GeV/c protons for fixed target and neutrino experiments



Experience, infrastructures and (some) detectors from NA48 to NA62

NA62-R_K Detector (inherited by NA48/2) and Data Taking



Magnetic spectrometer:

$\sigma_p/p = (0.48 \oplus 0.009\ p)\%$ (p in GeV/c)

Hodoscope:

Fast trigger for charged particle and timing for the event ($\sigma_t \sim 150$ps)

LKr electromagnetic calorimeter:

$\sigma_E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E in GeV)

$\sigma_x = \sigma_y \sim 1.5$mm for E=10 GeV

NA62 data taking :

- Four months in 2007 (mostly K^+ only)
- Two weeks in 2008 (special dataset for systematics uncertainties study)

R_K Measurement Strategy

- $K^\pm \to e^\pm \nu$ (K_{e2}), $K^\pm \to \mu^\pm \nu$ ($K_{\mu 2}$) collected simultaneously:
  - No dependence on K flux
  - Cancellation of several effects at first order

background events

downscaling factor of $K_{\mu 2}$

acceptance

LKr trigger efficiency

$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu 2}) - N_B(K_{\mu 2})} \cdot \frac{f_\mu \times A(K_{\mu 2}) \times \varepsilon(K_{\mu 2})}{f_e \times A(K_{e2}) \times \varepsilon(K_{e2})} \cdot \frac{1}{f_{LKR}}$$

signal events

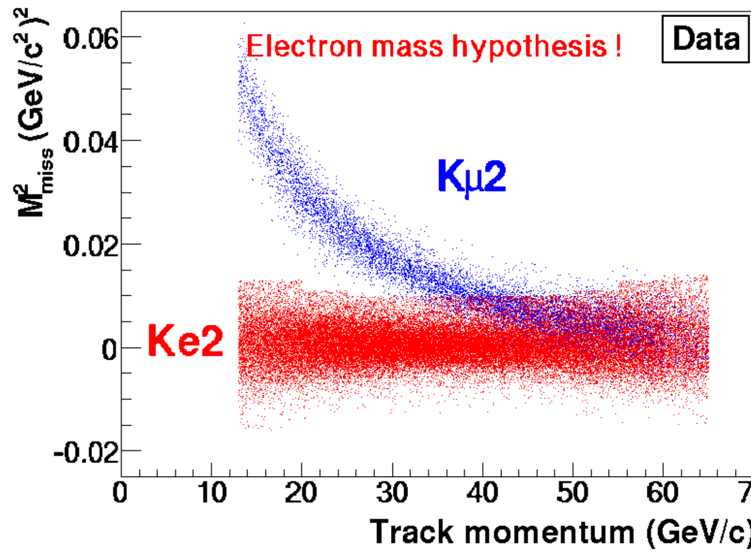
measured PID efficiency

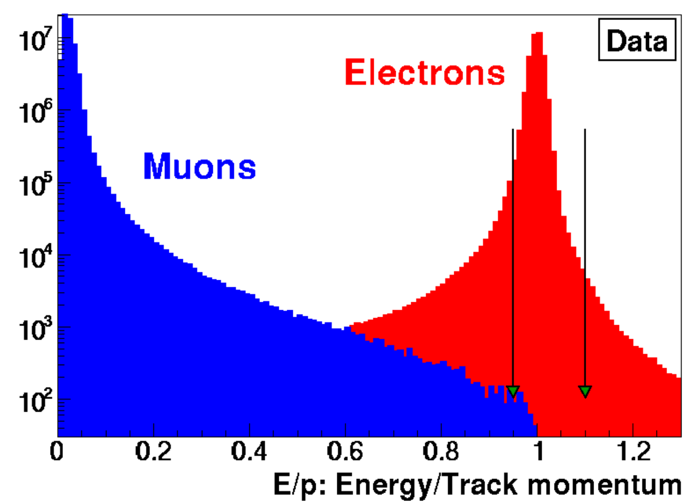
LKr readout efficiency

- Analysis performed in bins of the reconstructed lepton momentum

K_{e2} and $K_{\mu 2}$ Selection

- **Geometry**
  - One reconstructed charged track
  - $13 < p < 65$ [GeV/c]
  - Geometrical acceptance cut
  - Cut on K decay vertex position
  - Photon veto using LKr
- **Kinematics**
  - Missing mass: $M_{miss}^2(l)=(P_K-P_l)^2$
  - $-M_1^2<M_{miss}^2(l)< M_2^2$
- **Particle ID** (E_{LKR}/p_{spectr})
  - e ($(E/p)_{min} < E/p < 1.1$)
  - μ ($E/p < 0.85$)



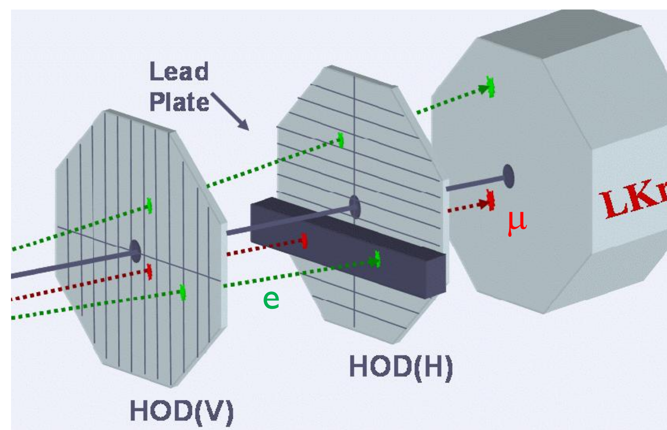


Background to K_{e2}

$K_{\mu 2}$ decay is the largest background source

- Catastrophic energy loss in or in front of the LKr
  $P_{\mu e}=P\ (\mu\rightarrow e) \sim 3\times 10^{-6} \Rightarrow P_{\mu e}/R_K \sim 10\%$
- $\mu^{\pm}\rightarrow e^{\pm}\nu\nu$ decays before the first DCH
  (suppressed by muon polarization effects)

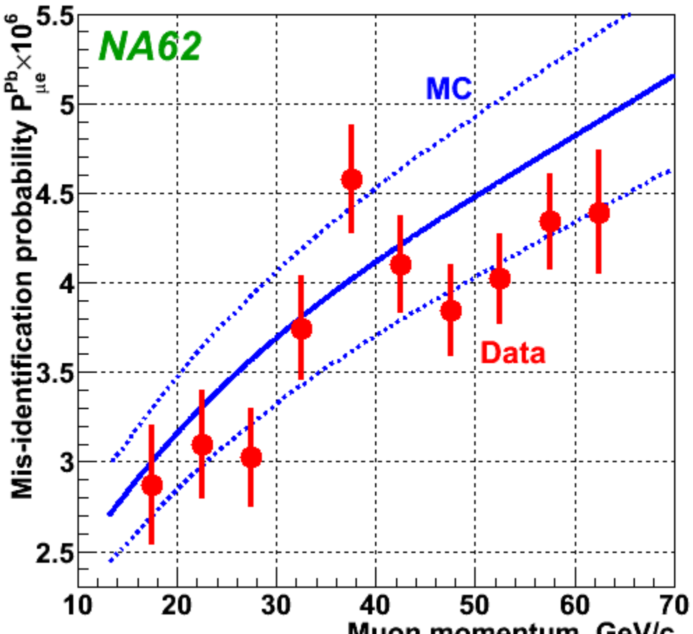
- Need direct measurement of $P_{\mu e}$
- To avoid electron contamination from muon decay ($\sim 10^{-4}$) a 9.2 X_0 thick lead wall covering 18% of the acceptance was installed between the HOD planes

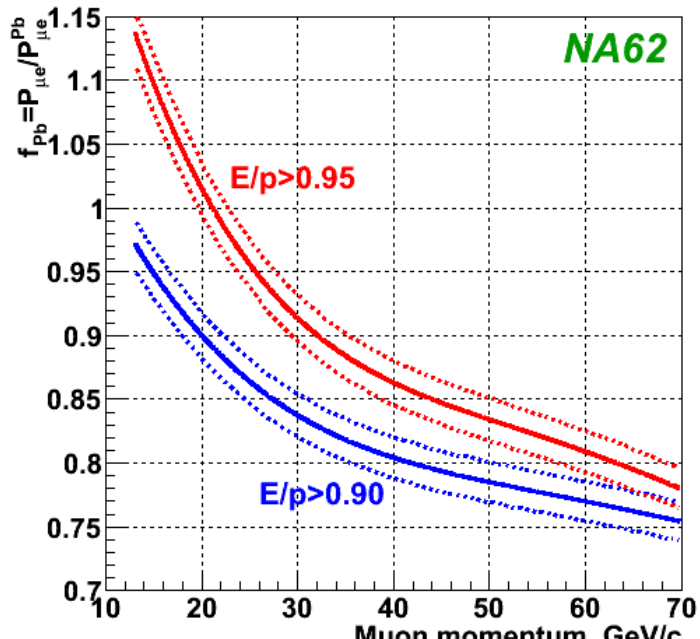


Background to K_{e2}

Muon catastrophic energy loss is the largest background source

- $P_{\mu e}$ is modified by the Pb wall
- The correction $f_{Pb} = P_{\mu e} / P_{\mu e}^{Pb}$ evaluated with a dedicated Geant4-based simulation





Background to K_{e2}

R_K is inclusive of IB radiation only $\Rightarrow$

the SD contribution must be carefully estimated and subtracted

- The structure-dependent (SD) $K^{\pm}\to e^{\pm}\nu\,\gamma$ process has two components: SD^{+} (positive photon helicity) and SD^{-} (negative photon helicity)
- SD^{-} decays and the interference between the IB and SD processes are negligible

  [J. Bijnens, G. Colangelo, G. Ecker, J. Gasser, arXiv:hep-ph/9411311]

- The SD^{+} background contribution has been estimated by MC simulation using a recent measurement of the $K^{\pm}\to e^{\pm}\nu\gamma$ (SD^{+}) differential decay rate

  [F. Ambrosino et al., Eur. Phys. J. C 65 (2010) 703]

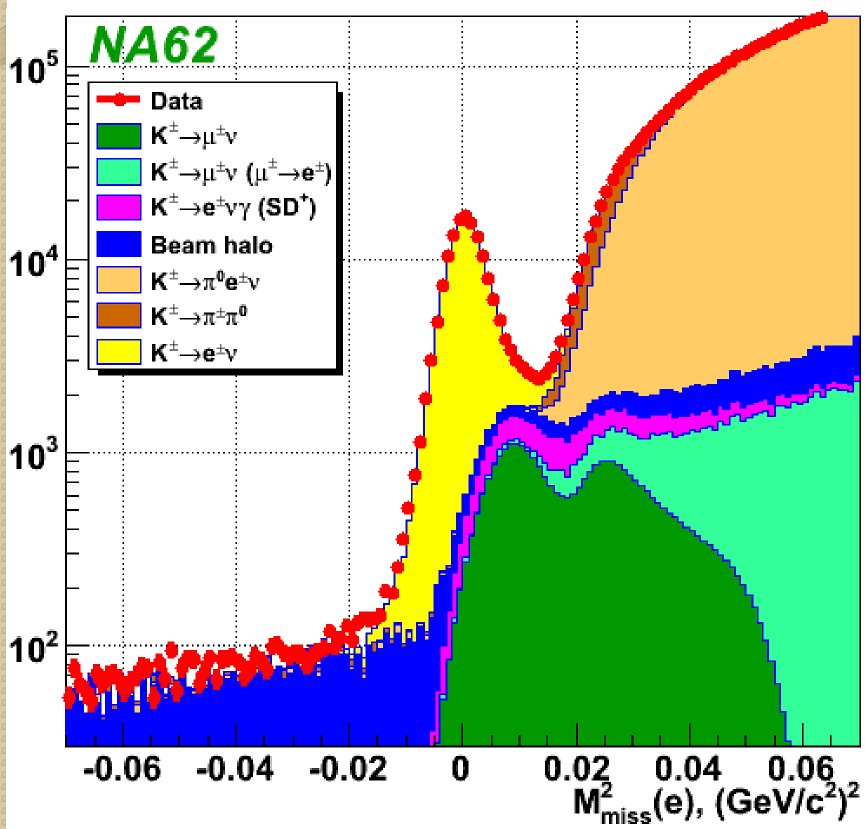
Background to K_{e2}

Background from beam halo muons has been directly measured on data

- K^+ only sample used to measure background in K^- sample and vice-versa
- K-less sample (both K^+ and K^- beams blocked, only muon halos alllowed)

  - Control samples normalized to the data in the M_{miss}^2 region populated mainly by beam halo events.
  - Probability to reconstruct a $K_{e2}^{\pm}$ candidate due to a $K^{\mp}$ decay with $e^{\pm}$ emission ($\sim 10^{-4}$) taken into account

K_{e2} Sample



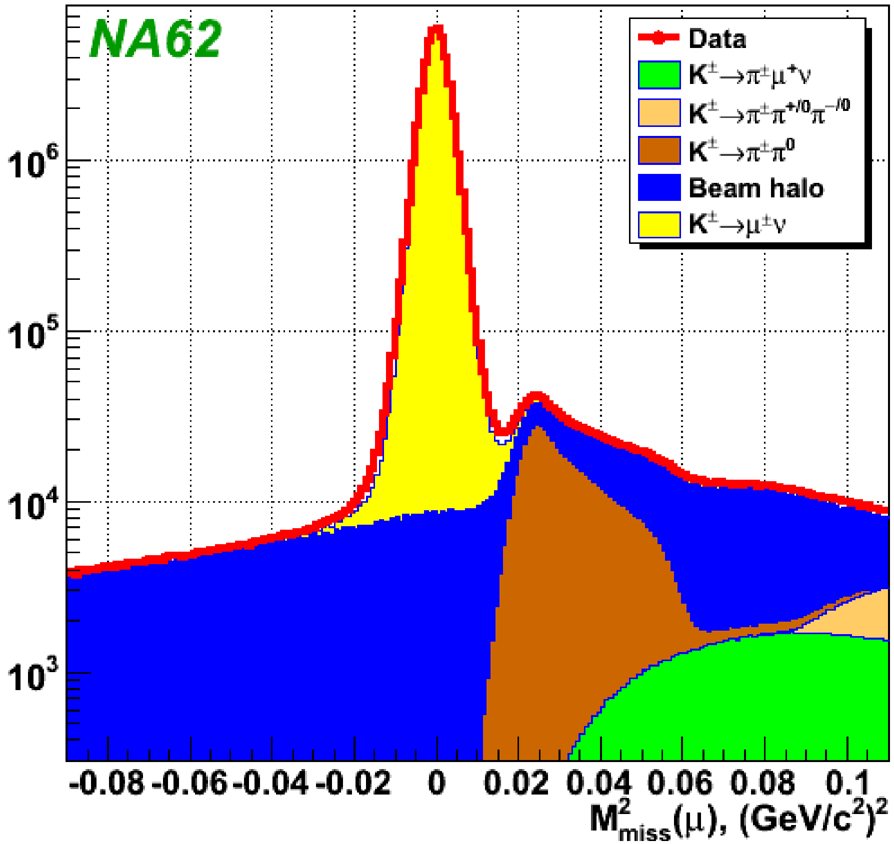
145,958 $K^{\pm} \to e^{\pm} \nu$ candidates

(99.28±0.05)% $e^{\pm}$ ID efficiency

Decay	B/(S+B)
$K^{\pm} \to \mu^{\pm}\nu$	(5.64 ± 0.20)%
$K^{\pm} \to \mu^{\pm}\nu$ ($\mu \to e$)	(0.26 ± 0.03)%
$K^{\pm} \to e^{\pm}\nu\gamma$ (SD^{+})	(2.60 ± 0.11)%
$K^{\pm} \to \pi^{0}_{D} e^{\pm}\nu$	(0.18 ± 0.09)%
$K^{\pm} \to \pi^{\pm}\pi^{0}_{D}$	(0.12 ± 0.06)%
Wrong sign K	(0.04 ± 0.02)%
Beam halo	(2.11 ± 0.09)%
Total	(10.95 ± 0.27)%

$K_{\mu 2}$ Sample

The only significant background source in the $K_{\mu 2}$ sample is the beam halo measured using the same technique as for the K_{e2} sample



$42.817 \cdot 10^6$ $K^{\pm} \to \mu^{\pm} \nu$ candidates (collecting with downscaling factor D=50 or D=150)

$B/(S+B) = (0.50 \pm 0.01)\%$

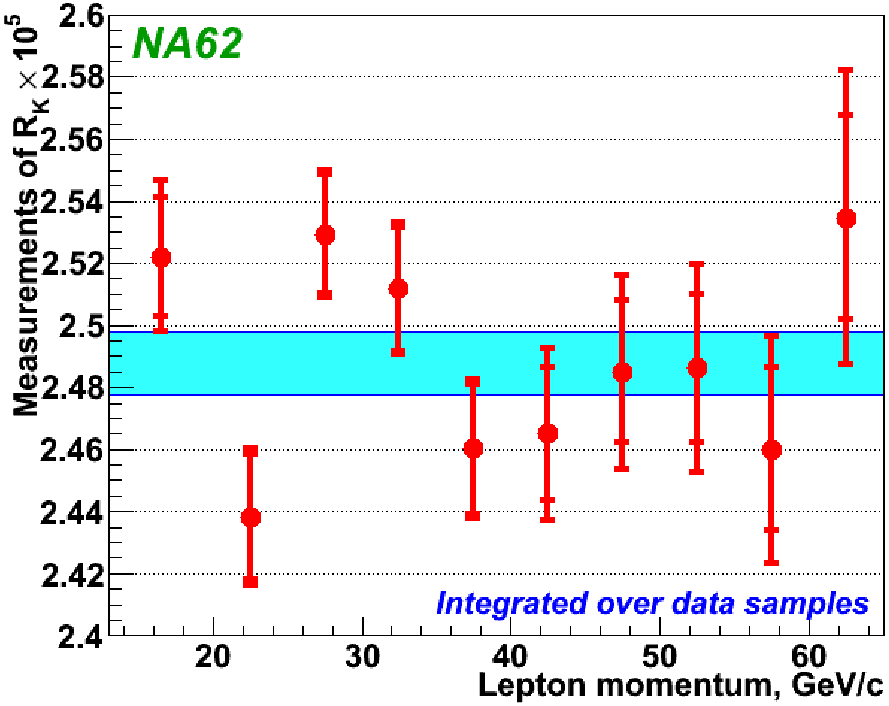
NA62 Result (full data set)

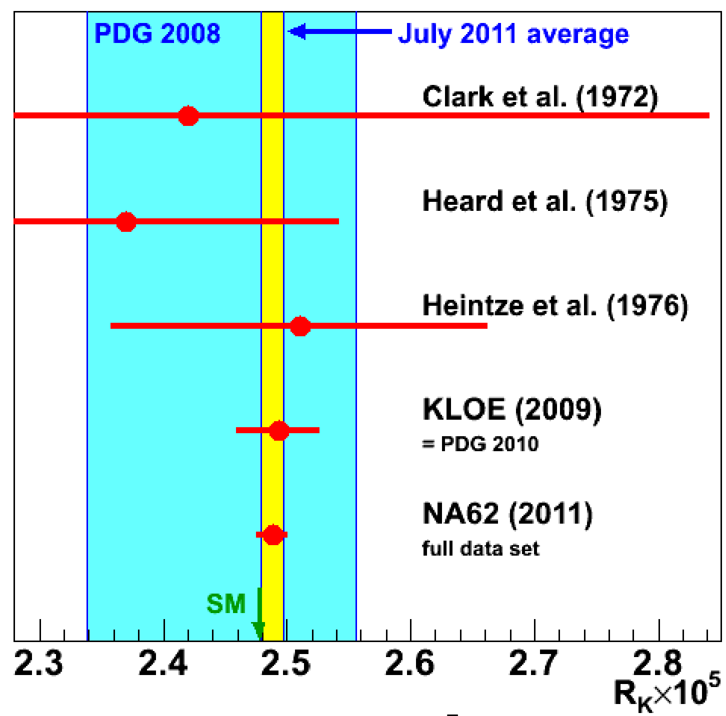
Fit over 40 R_K measurements (4 data samples × 10 momentum bins)

including correlations: χ^2/ndf=47/39

July 2011

$R_K=(2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}=(2.488 \pm 0.010) \times 10^{-5}$



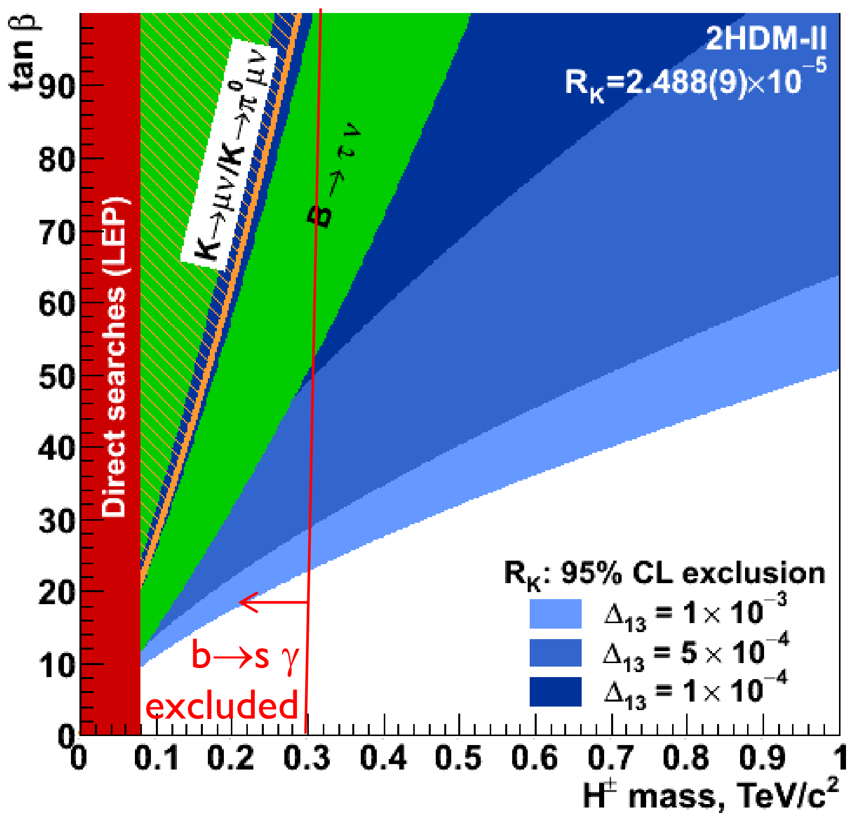


July 2011 world average : $R_K= (2.488 \pm 0.009) \times 10^{-5}$

R_K Sensitivity to New Physics

For non-tiny values of the LFV s-lepton mixing Δ_{13}

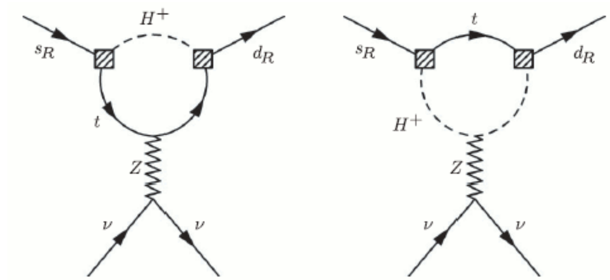
the sensitivity to $H^{\pm}$ in R_K is strong



K→ πνν in MSSM

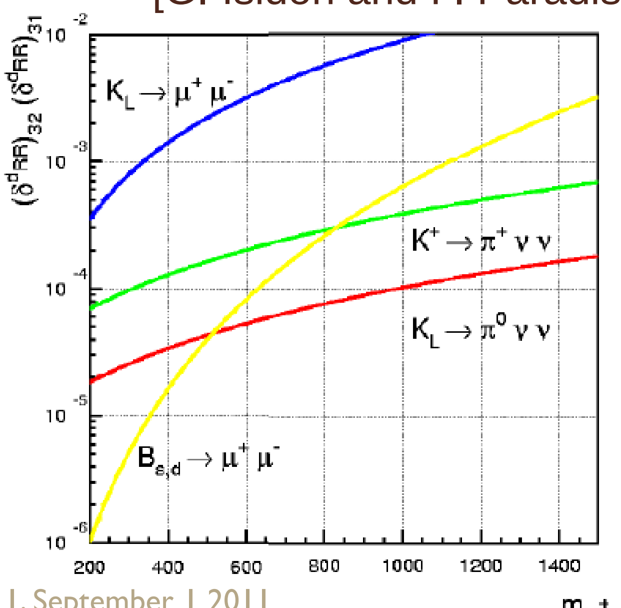
Charged Higgs/top quark loops at large tanβ and with

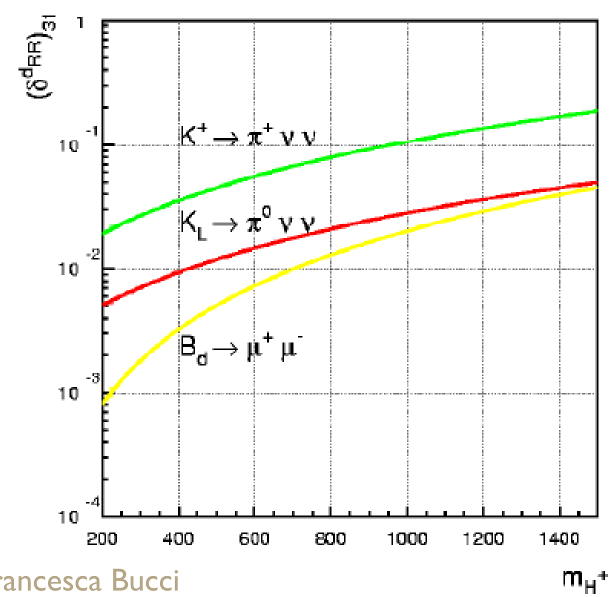
non-MFV right-right breaking terms



can induce sizable modifications of K→πνν amplitudes

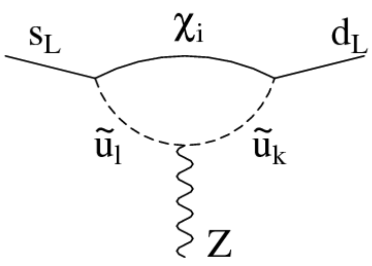
[G. Isidori and P. Paradisi, Phys. Rev. D73 (2006) 055017]

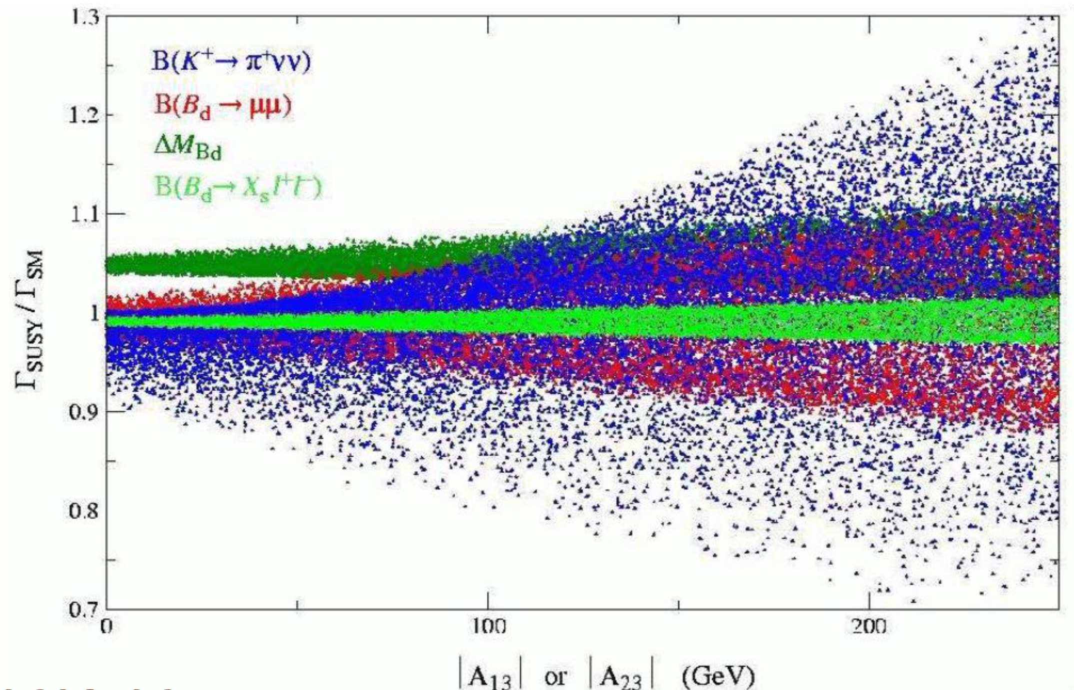




K→ πνν in MSSM

Non-standard model effects induced by chargino-squarks loop in the presence of non-MFV up-type trilinear terms are maximal in the K→ πνν decays



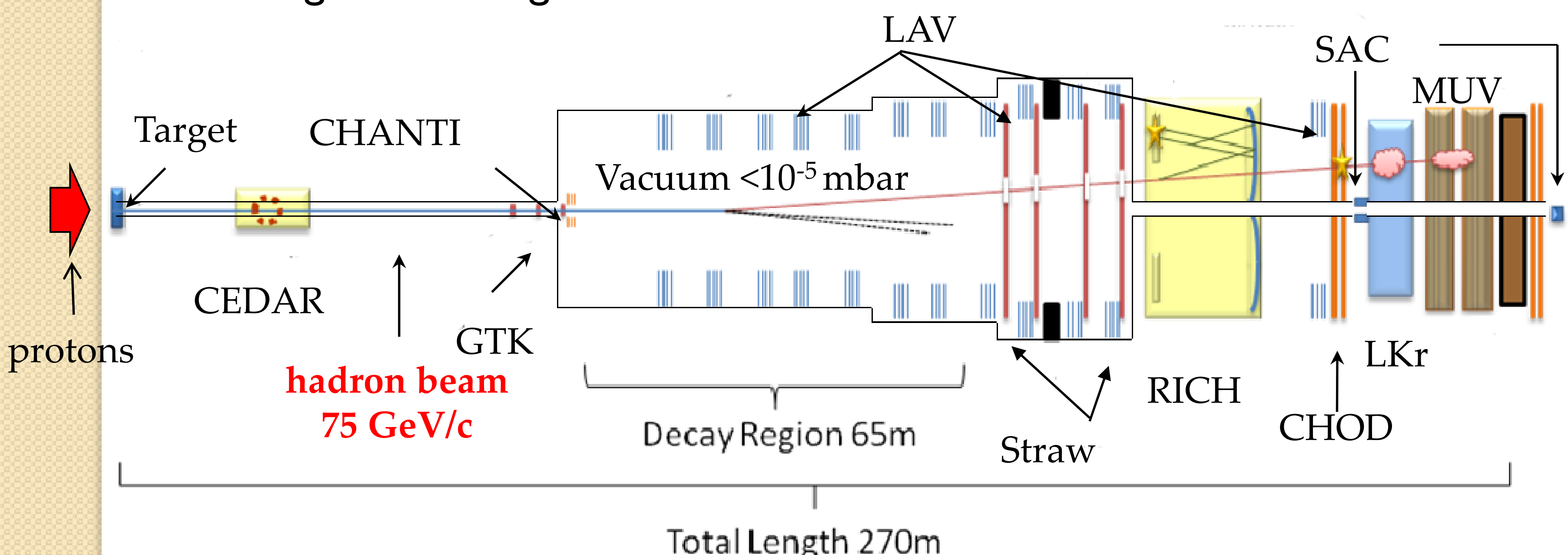


[G. Isidori et al. JHEP 0608:064 (2006)]

NA62

Branching ratio measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ with 10% accuracy

- O(100) $K^+ \to \pi^+ \nu\bar{\nu}$ events (2 years of data taking)
- 10/1 signal to background ratio



- End 2012: first technical run
- Physics data taking driven by CERN accelerator schedule

Conclusions

- R_K measurement:
  - The analysis of the full data sample taken by NA62 completed
  - The measured value is $R_K=(2.488 \pm 0.010) \times 10^{-5}$
  - The precision achieved is 0.4%
  - The NA62 could improve the precision down to 0.2%

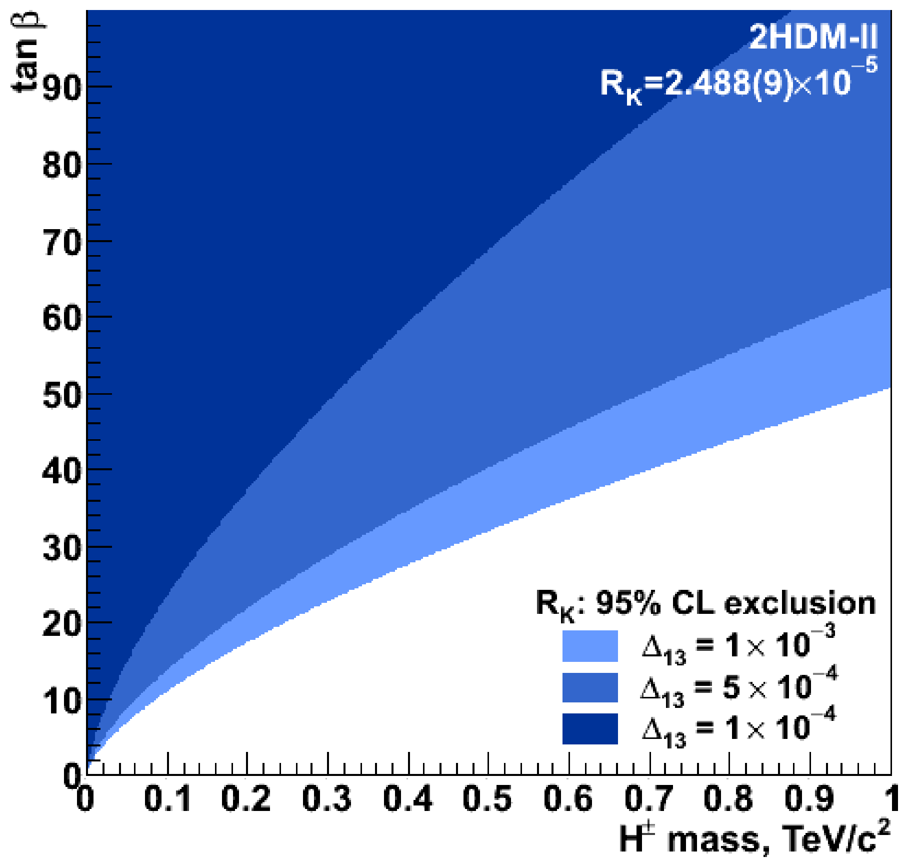
- $B(K^+ \rightarrow \pi^+ \nu\nu)$ measurement with NA62:
  - High sensitivity to New Physics
  - 10% precision BR measurement expected in two years of data taking
  - **Experiment under construction**

Backup Slides

R_K Sensitivity to New Physics

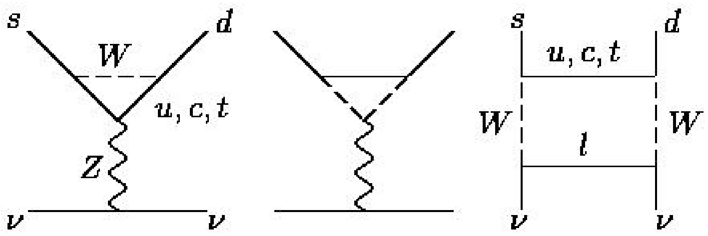
For non-tiny values of the LFV s-lepton mixing Δ_{13}

the sensitivity to $H^{\pm}$ in R_K is strong



$K \to \pi \nu \bar{\nu}$ Decays

- FCNC decays mediated by Z penguins and box diagrams → strongly suppressed in the SM ($<10^{-10}$)



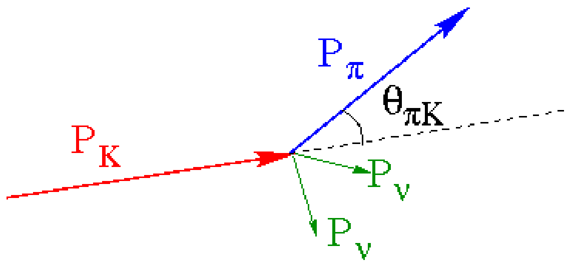
- Calculable with excellent precision [Phys.Rev. D83 (2011) 034030]

$$BR\left(K^+ \to \pi^+ \nu \bar{\nu}\right) = \left(7.81 \pm 0.75 \pm 0.29\right) \times 10^{-11}$$
$$BR\left(K_L \to \pi^0 \nu \bar{\nu}\right) = \left(2.43 \pm 0.39 \pm 0.06\right) \times 10^{-11}$$

Background Rejection

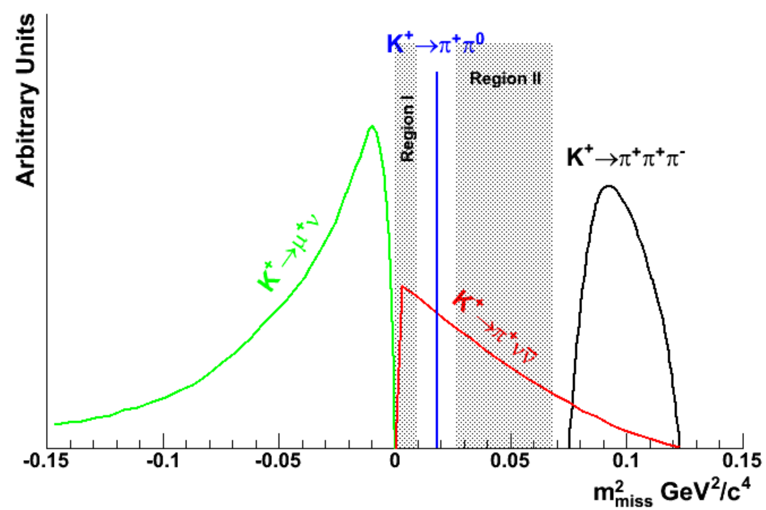
Signal signature:

- Incoming high momentum(75 GeV/c) K^+
- Outgoing low momentum(<35 GeV/c) π^+ in time with the incoming K^+



$$m^2_{miss} \cong m^2_K\left(1-\frac{|P_\pi|}{|P_K|}\right)+m^2_\pi\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\theta^2_{\pi K}$$

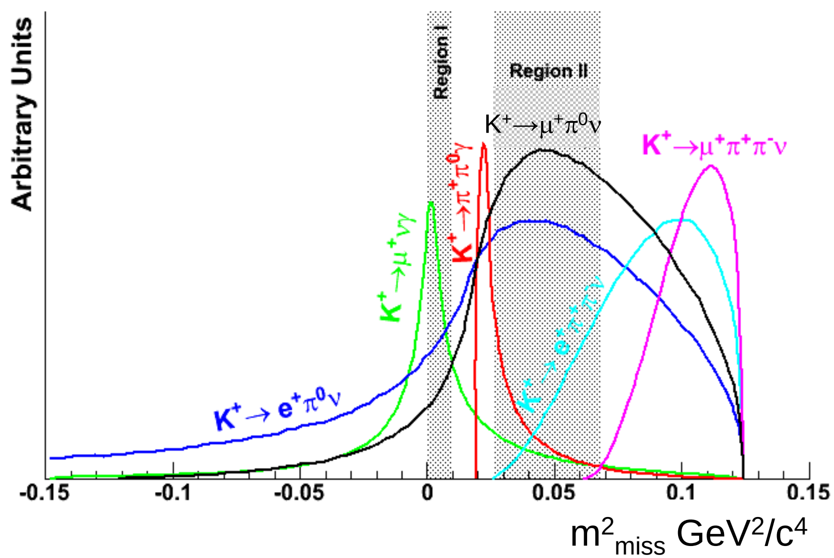
Decay	BR
$K^+\to\mu^+\nu(K_{\mu 2})$	0.64
$K^+\to\pi^+\pi^0(K_{\pi 2})$	0.21
$K^+\to\pi^+\pi^+\pi^-$ $K^+\to\pi^+\pi^0\pi^0$	0.07



~92% of kaon decays kinematically constrained

Particle Identification

- K^+ positive identification (CEDAR)
- π/μ separation (RICH)
- π/e separation (E/p)



Decay	BR
$K^+\to\pi^0e^+\nu(K_{e3})$	0.051
$K^+\to\pi^0\mu^+\nu(K_{\mu3})$	0.034
$K^+\to\mu^+\nu\gamma(K_{\mu2\gamma})$	6.2×10^{-3}
$K^+\to\pi^+\pi^-e^+\nu\ (K_{e4})$	4.1×10^{-5}
$K^+\to\pi^+\pi^-\mu^+\nu\ (K_{\mu4})$	1.4×10^{-5}

Sensitivity

Decay Mode	Events
Signal: $K^+\to\pi^+\nu\nu$ *[flux = 4.8×10¹² decay/year]*	55 *evt/year*
$K^+\to\pi^+\pi^0$ $[\eta_{\pi 0} = 2\times10^{-8}\ (3.5\times10^{-8})\ ]$	4.3% (7.5%)
$K^+\to\mu^+\nu$	2.2%
$K^+\to e^+\pi^+\pi^-\nu$	≤3%
Other 3 – track decays	≤1.5%
$K^+\to\pi^+\pi^0\gamma$	~2%
$K^+\to\mu^+\nu\gamma$	~0.7%
$K^+\to e^+(\mu^+)\ \pi^0\nu$, others	negligible
Expected background	≤13.5% (≤17%)

Definition of "year" and running efficiencies based on NA48 experience:
~100 days/year and 60% overall efficiency

Techniques for $K^+ \to \pi^+ \nu \bar{\nu}$

Stopped

- Work in kaon frame
- High kaon purity
- Compact detectors

In-Flight

- Decays in vacuum
- RF separated or not separated beams
- Extended decay regions

Exp	Machine	Meas. or UL 90% CL	Notes
	Argonne	$<5.7\times10^{-5}$	Stopped; HL Bubble Chamber
	Bevatron	$<5.6\times10^{-7}$	Stopped; Spark Chambers
	KEK	$<1.4\times10^{-7}$	Stopped; $\pi^+ \to \mu^+ \to e^+$
E787/E949	AGS	$(1.73^{+1.15}_{-1.05})\times10^{-10}$	Stopped
NA62	SPS		In Flight; Unseparated
P996	FNAL		Stopped; Tevatron as strecher ring?

$K_L^0 \to \pi^0 \nu \bar{\nu}$

The charm contribution can be fully neglected since it proceeds in the SM almost entirely through direct CP violation → determination of η

Exp	Machine	Meas. or UL 90% CL	Notes
KTeV	Tevatron	$<5.7\times10^{-7}(\pi^0 \to ee\gamma)$	
E391a	KEK-PS	$<2.6\times10^{-8}$	
KOTO	J-PARC		Aim at 2.7 SM evts/3y
KOPIO			Opportunity at Project X ?

Need a huge number of K_L decays
NA48 K_L flux corresponding to 3×10^{10}/year
NA62 possible K_L flux 5-10 times NA48 one
After SPS upgrade 100 times more